Solar Energy Materials & Solar Cells 160 (2017) 141–148

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

From randomly self-textured substrates to highly efficient thin film solar cells: Influence of geometric interface engineering on light trapping, plasmonic losses and charge extraction

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ARTICLE INFO

Keywords:
Interfaces
Light trapping
Plasmonics
Zinc oxide
Microcrystalline silicon
Crack formation

ABSTRACT

An approach that models the fabrication and enables the characterization of randomly self-textured silicon thin film solar cells is developed and are compared to experimental results. The optical and electrical properties of the solar cells depend on the morphology of the randomly self-textured substrate and the formation of the individual layers of the solar cell. The influence of the interface morphology on the optical and electrical properties is investigated by 3D morphological algorithms. The calculated interface morphologies are compared to measured surfaces, and used as input parameters to simulate the optical wave propagation and to determine the formation of regions with reduced order (cracks) in the solar cells. The calculations are compared to experimentally realized 1.1 µm thick microcrystalline silicon solar cells prepared on randomly self-textured substrates with high energy conversion efficiency of up to 9.4%. Guidelines for the optical and electronic optimization are provided.

1. Introduction

Thin film solar cells are promising devices for harvesting the solar energy. Silicon thin film solar cells can be fabricated on large areas at low costs utilizing synergies with flat panel display technologies [1–4]. The realization of silicon thin film solar cells with high energy conversion efficiencies is limited by the low absorption coefficient in the red and near-infrared part of the optical spectrum [5]. In order to achieve high short circuit current densities, efficient light trapping and photon management schemes have been developed [6–10]. Commonly, the absorption of light is enhanced by texturing the front or back contact of the solar cells [6–10]. The textured front contact has the function of improving the incoupling and scattering of the incident light. The back contact textures should elongate the optical path length of the light that reaches the back reflector, ideally without increasing optical losses of the back contact [11–17]. Furthermore, to realize solar cells with high energy conversion efficiencies, the fill factor and open circuit voltage have to be maximized. The fill factor and open circuit voltage are negatively affected by recombination centers, which are formed during the growth of the microcrystalline silicon film [6,18–24]. A high concentration of recombination centers occurs in porous regions or regions with reduced structural order, often called cracks or voids. Such cracks are formed preferably if the microcrystalline silicon films are prepared on textured substrates. Films deposited on flat or smooth substrates exhibit few or almost no cracks. With increasing roughness of the substrates the concentration of cracks in the microcrystalline silicon film is increased [23]. The Institute of Microengineering in Neuchâtel has developed a process to engineer the surface of randomly textured substrates by using an argon plasma treatment [6]. Similar plasma treatments have been carried out to smoothen the surface of dielectrics deposited by plasma enhanced chemical vapor deposition (PECVD) like silicon oxide and silicon nitride [25,26]. During the plasma treatment the textured substrate is etched and the surface textures are smoothened out, which is shown in Fig. 1. The typical V-shaped surface textures of the zinc oxide (ZnO) substrate prepared by low pressure chemical vapor deposition (LPCVD) (Fig. 1(a)) are changed to U-shaped surface features (Fig. 1(b)). By varying the plasma treatment time the morphology of the substrate is engineered and the surface roughness can be controlled. As a consequence, the interface morphology of the microcrys-

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http://dx.doi.org/10.1016/j.solmat.2016.10.005
Received 3 May 2016; Received in revised form 28 September 2016; Accepted 3 October 2016
Available online 26 October 2016
0927-0248/

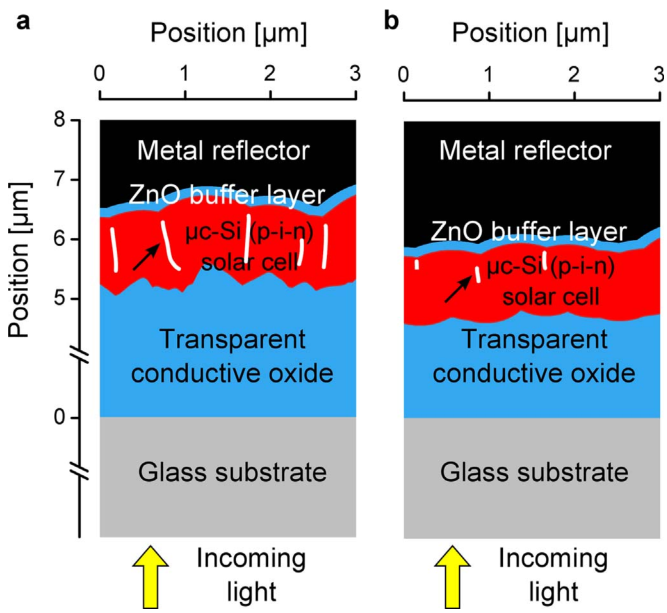

Fig. 1. Cross section of microcrystalline silicon solar cell prepared on a randomly textured LPCVD ZnO substrate (a) prior and (b) post argon plasma treatment. White lines indicate regions where cracks are formed.

talline silicon layers is changed, and the concentration of cracks in the film is reduced (white lines in Fig. 1). Hence, the argon plasma treatment affects the optical and electrical properties of the solar cells.

The aim of this study is to investigate the trade-off between light trapping and the formation of cracks in microcrystalline silicon solar cells prepared on LPCVD ZnO substrates. Light trapping and crack formation are studied for different argon treatment times of the ZnO substrate. The light trapping and photon management is investigated experimentally and by optical simulations. The developed 3D morphological algorithms are used to model the manufacturing process of the solar cells. The algorithms model the argon plasma treatment of the randomly textured ZnO substrate and the deposition of the solar cell layers. Up to our knowledge, for the first time the argon plasma treatment is modeled by an isotropic etching process. The calculated interface morphologies are used as input parameters for the optical simulation of the solar cells. The optical simulations allow for determining the influence of the surface texture on light trapping and plasmonic losses of the back reflector. Previously, we have modeled the optics of amorphous silicon solar cells on randomly and periodically textured substrates by using realistic interface morphologies, but simulation results have not been compared to experimental results [27,28]. In this study, to our knowledge, for the first time optical simulations of randomly textured microcrystalline silicon solar cells using realistic interface morphologies are compared to experimentally realized solar cells. Furthermore, the electrical characteristics of the solar cells are studied by experiment and a simple analytical model, which determines the formation of cracks in the silicon films from the calculated interface morphologies. An image segmentation algorithm is used to extract the average dimensions of the interface morphology of textured ZnO substrates. Afterwards, the extracted dimensions are used to calculate an average critical thickness. The average critical thickness can be correlated with the crack density in the film. If the average critical thickness is larger than the solar cell thickness, the density of cracks in the film is small, while in the opposite case a high crack density exists in the film. A summary of the simulation process flow is given in Fig. 2. The calculated interface morphologies are used as input parameters in determining the optical and the electrical properties of the self-textured solar cells. The left branch represents the optical simulation process flow, while the right branch describes the process flow to determine the electrical properties.

The fabrication of the textured substrate and solar cells is described in Section 2. Furthermore, experimental results of microcrystalline silicon solar cells on argon plasma treated ZnO substrates are presented in Section 2. The 3D morphological algorithms and optical simulation model used to determine the light propagation are introduced in Section 3, while the simulation results are described in Section 4. The influence of the substrate morphology on the charge collection and crack formation is described in Section 5, followed by a summary of the results in Section 6.

2. Device fabrication and experimental results

The fabrication process starts by preparing a boron-doped LPCVD ZnO:B layer on top of a 0.5 mm thick Schott glass substrate [6,9,19,29,30]. The ZnO layer has a thickness of 5 µm, and it is characterized by the formation of randomly oriented pyramidal surface features. An atomic force microscope (AFM) image of the ZnO substrate is shown in Fig. 3(a). The size of the features increases with the thickness of the ZnO film [19]. In the next step, the ZnO:B films are subjected to an argon (Ar) plasma treatment by a reactive ion etching (RIE) system, at a power density of 1 W/cm^2, pressure of 80 µbar and excitation frequency of 13.56 MHz. With different argon treatment time of 20, 45 and 80 min the surface textures of the ZnO substrates are engineered as shown in Fig. 3(b), (c) and (d), respectively. Details on the plasma treatments of ZnO substrates can be found in literature [6,9,19,30]. Details on the dimensions of the surface textures depending on the argon treatment time are given later in the manuscript.

Previous studies have shown that solar cells prepared on untreated substrates exhibit the highest density of cracks [9,19]. Solar cells with high crack density are characterized by low energy conversion efficiencies and a large variance of the solar cell parameters not allowing for a reliable analysis. Therefore, in this study the solar cells have been fabricated only on substrates treated by argon plasma. The microcrystalline silicon p-i-n solar cells are prepared by a PECVD process [31,32]. The p-, i- and n- layers of the fabricated microcrystalline silicon diodes have a thickness of 20 nm, 1100 nm and 20 nm, respectively. The p- and n-layers are used to separate the photogenerated charge carriers. The thickness of the p- and n-layers is minimized to reduce the optical losses of the contact layers. In the last fabrication step, the back contact is formed. The back contact consists of a 150 nm thick ZnO buffer layer prepared by LPCVD and a silver (Ag) reflector prepared by sputtering at room temperature. The ZnO buffer layer can also be deposited by sputtering, but LPCVD ZnO has been chosen because it avoids ion-damage to the n-layer in order to remain compatible with the standard solar cell process commonly used by the Institute of Microengineering in Neuchâtel.

The interface morphology of the silver back reflector has a distinct influence on the plasmonic losses in the solar cells, specially in the presence of nanofeatures [9,11–17,33]. Such nanofeatures can be caused by the deposition of the microcrystalline silicon solar cell or the ZnO buffer layer, and in this study, the later is the cause for the nanofeatures formation [9,11–17,33]. These nanotextures are responsible for plasmonic losses, so that the quantum efficiency and short circuit current density are reduced [9,12,13,17]. To reduce the plasmonic losses in this study, most of the nanofeatures of the LPCVD ZnO buffer layer are removed by surface engineering. This is achieved by a 10 min argon plasma treatment of the ZnO buffer layer prior to the deposition of the silver film [9].

A summary of the measured parameters for fabricated solar cells is given in Table 1. The short circuit current density drops with increasing plasma treatment time, while the fill factor and open circuit voltage increase. When increasing the plasma treatment time from 20 min to 80 min, the short circuit current density decreases by 6%, while the fill factor and open circuit voltage increase by 8.5% and 6%, respectively. As a consequence, the plasma treatment of 80 min exhibits the energy conversion efficiency of 9.4%, which represents one of the highest